

NEUTRINO PHYSICS: STATUS AND PROSPECTS

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This pedagogical overview will cover the current status of neutrino physics from an experimentalist's point of view, focusing primarily on oscillation studies. The evidence for neutrino oscillations will be presented, along with the prospects for further refinement of observations in each of the indicated regions of two-flavor oscillation parameter space. The next steps in oscillation physics will then be covered (under the assumption of three-flavor mixing): the quest for θ_{13} , mass hierarchy and, eventually, leptonic CP violation. Prospects for non-oscillation aspects of neutrino physics, such as kinematic tests for absolute neutrino mass and double beta decay searches, will also be discussed briefly.

1. Neutrinos and Weak Interactions

Neutrinos, the lightest of the fundamental fermions, are the neutral partners to the charged leptons. In the current picture, they come in three flavors (e , μ , τ)^a and interact only via the weak interaction. In the Standard Model of particle physics, neutrinos interact with matter in two ways: in a *charged current* interaction, the neutrino exchanges a charged W^\pm boson with quarks (or leptons), producing a lepton of the same flavor as the interacting neutrino (assuming there is enough energy available to create the lepton.) In a *neutral current* interaction, a neutral Z boson is exchanged; this type of interaction is *flavor-blind*, *i.e.* the rate does not depend on the flavor of neutrino (see Figure 1.)

2. Neutrino Mass and Oscillations

Neutrinos are known to be very much lighter than their charged lepton partners; direct measurements of neutrino mass yield only upper limits of

^aThe τ neutrino has only recently been directly detected by the DONUT experiment¹.

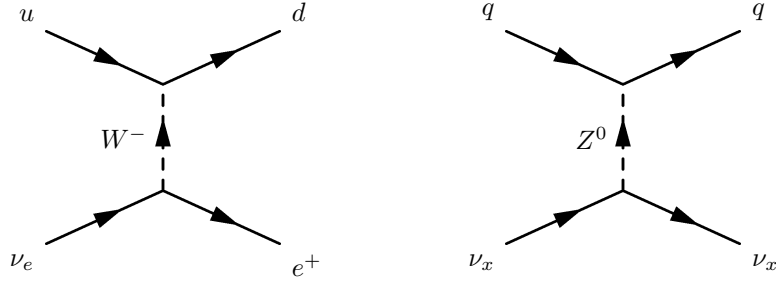


Figure 1. Examples of CC (left) and NC (right) neutrino interactions.

$< 2 \text{ eV}/c^2$. However, the question of neutrino mass can be probed using the oscillatory behavior of free-propagating neutrinos, which is dependent on the existence of non-zero neutrino mass.

Neutrino oscillations arise from straightforward quantum mechanics. We assume that the N neutrino flavor states $|\nu_f\rangle$, which participate in the weak interactions, are superpositions of the mass states $|\nu_i\rangle$, and are related by the Maki-Nakagawa-Sakata (MNS) unitary mixing matrix:

$$|\nu_f\rangle = \sum_{i=1}^N U_{fi} |\nu_i\rangle. \quad (1)$$

For the two-flavor case, assuming relativistic neutrinos, it can easily be shown that the probability for flavor transition is given by

$$P(\nu_f \rightarrow \nu_g) = 1 - |\langle \nu_f | \nu_g \rangle|^2 = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E), \quad (2)$$

for $\Delta m^2 \equiv m_2^2 - m_1^2$ (in eV^2) and with θ the angle of rotation. L (in km) is the distance traveled by the neutrino and E (in GeV) is its energy.

Several comments are in order:

- Note that in this equation the *parameters of nature* that experimenters try to measure (and theorists try to derive) are $\sin^2 2\theta$ and Δm^2 . L and E depend on the experimental situation.
- The neutrino oscillation probability depends on mass squared differences, *not* absolute masses.
- In the three-flavor picture, the transition probabilities can be computed in a straightforward way. The flavor states are related to the mass states according to

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (3)$$

and the transition probability is given by

$$\begin{aligned} P(\nu_f \rightarrow \nu_g) = & \\ & \delta_{fg} - 4 \sum_{j>i} \text{Re}(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin^2(1.27 \Delta m_{ij}^2 L/E) \\ & \pm 2 \sum_{j>i} \text{Im}(U_{fi}^* U_{gi} U_{fj} U_{gj}^*) \sin^2(2.54 \Delta m_{ij}^2 L/E), \end{aligned}$$

again for L in km, E in GeV, and Δm^2 in eV^2 . The $-$ refers to neutrinos and the $+$ to antineutrinos.

- For three mass states, there are only two **independent** Δm_{ij}^2 values.
- If the mass states are not nearly degenerate, one is often in a “decoupled” regime where it is possible to describe the oscillation as effectively two-flavor, i.e. following an equation similar to 2, with effective mixing angles and mass squared differences. We will assume a two-flavor description of the mixing for most cases here.
- “Sterile” neutrinos, ν_s , with no normal weak interactions, are possible in many theoretical scenarios (for instance, as an isosinglet state in a GUT.)
- When neutrinos propagate in matter, the oscillation probability may be modified. This modification is known as the the “Mikheyev-Smirnov-Wolfenstein (MSW) effect” or simply the “matter effect”. Physically, neutrinos acquire effective masses via virtual exchange of W bosons with matter (virtual CC interactions.) For example, consider ν_e propagating through solar matter: electron neutrinos can exchange W’s with electrons in the medium, inducing an effective potential $V = \sqrt{2} G_F N_e$, where N_e is the electron density. Muon and τ -flavor neutrinos, however, can exchange virtual Z bosons only with the matter (because there are no μ ’s and τ ’s present.) The probability of flavor transition may be either enhanced or suppressed in a way which depends on the density of matter traversed (and on the vacuum oscillation parameters.) A description of the phenomenology of neutrino matter effects may be found in *e.g.* References ^{2,3}. We will see below that matter ef-

fects become important for the solar neutrino oscillation case, and also for future long baseline experiments.

2.1. *The Experimental Game*

The basic experiment to search for neutrino oscillations can be described very simply.

- (1) Start with some source of neutrinos, either natural or artificial.
- (2) Calculate (or better yet, measure) the flavor composition and energy spectrum of neutrinos.
- (3) Let the neutrinos propagate.
- (4) Measure the flavor composition and energy spectrum after propagation. Have the flavors and energies changed? If so, is the change described by the oscillation equation 2? And if so, what are the allowed parameters?

The signature of neutrino oscillation manifests itself in one of two ways, either by disappearance or appearance. In “disappearance” experiments, neutrinos appear to be lost as they propagate, because they oscillate into some flavor with a lower interaction cross-section with matter. An example of disappearance is a solar neutrino experiment, for which ν_e transform into muon/tau flavor neutrinos, which are below CC interaction threshold at solar neutrino energies of a few MeV (solar ν_e ’s do not have enough energy to create μ or τ leptons.) In “appearance” experiments, one directly observes neutrinos of a flavor not present in the original source. For example, one might observe τ ’s from ν_τ in a beam of multi-GeV ν_μ .

3. The Experimental Evidence

There are currently three experimental indications of neutrino oscillations. These indications are summarized in Table 1. We will now examine the current status of each of these observations.

3.1. *Atmospheric Neutrinos*

Atmospheric neutrinos are produced by collisions of cosmic rays (which are mostly protons) with the upper atmosphere. Neutrino energies range from about 0.1 GeV to 100 GeV. At neutrino energies $\gtrsim 1$ GeV, for which the geomagnetic field has very little effect on the primary cosmic rays, by geometry the neutrino flux should be up-down symmetric. Although

ν source	Experiments	Flavors	E	L	Δm^2 sensitivity (eV^2)
Sun	Chlorine	$\nu_e \rightarrow \nu_x$	5-15 MeV	10^8 km	$10^{-12} - 10^{-10}$
	Gallium				or $10^{-6} - 10^{-3}$
Reactor	Water Cherenkov Scintillator	$\bar{\nu}_e \rightarrow \bar{\nu}_x$	3-6 MeV	~ 180 km	$10^{-5} - 10^{-3}$
Cosmic ray showers	Water Cherenkov	$\nu_\mu \rightarrow \nu_x$	0.1-100 GeV	$10 - 10^5$ km	$10^{-2} - 10^{-3}$
	Iron calorimeter Upward muons				
Accelerator	LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	15-50 MeV	30 m	0.1-1

the absolute flux prediction has $\sim 15\%$ uncertainty, the flavor ratio (about two muon neutrinos for every electron neutrino) is known quite robustly, since it depends on the well-understood decay chain $\pi^\pm \rightarrow \mu^\pm \nu_\mu(\bar{\nu}_\mu) \rightarrow e^\pm \nu_e(\bar{\nu}_e) \bar{\nu}_\mu(\nu_\mu)$. The experimental strategy is to observe high energy interactions of atmospheric neutrinos, tagging the flavor of the incoming neutrino by the flavor of the outgoing lepton, which can be determined from the pattern of energy loss: muons yield clean tracks, whereas high-energy electrons shower. Furthermore, the direction of the produced lepton follows the direction of the incoming neutrino, so that the angular distribution reflects the neutrino pathlength distribution.

Super-Kamiokande⁴, a large water Cherenkov detector in Japan, has shown a highly significant deficit of ν_μ events from below⁵, with an energy and pathlength dependence as expected from equation 2 (see Figure 2.) The most recent data constrain the two-flavor $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters to a region as shown in Figure 3. The latest results from Soudan 2⁶ (an iron tracker) and from MACRO's⁷ upward-going muon sample are consistent with the Super-K data.

Super-K has also been able to shed some light on the flavors involved in the atmospheric ν_μ disappearance. Assuming a two-flavor oscillation, the missing ν_μ 's could have oscillated into either ν_e , ν_τ or ν_s . The oscillation cannot be pure $\nu_\mu \rightarrow \nu_e$, because there is no significant excess of ν_e from below. In addition, the CHOOZ¹⁰ and Palo Verde¹¹ experiments have ruled out disappearance of reactor $\bar{\nu}_e$; only small mixing to ν_e is allowed⁸. (see Section 6.1.)^b

The $\nu_\mu \rightarrow \nu_\tau$ hypothesis is difficult to test directly. Super-K expects relatively few charged current (CC) ν_τ interactions, and the products of such interactions in the detector are nearly indistinguishable from other atmo-

^bIn fact, a potential small $\nu_\mu \rightarrow \nu_e$ mixing is extremely interesting, as we will see in Section 6.

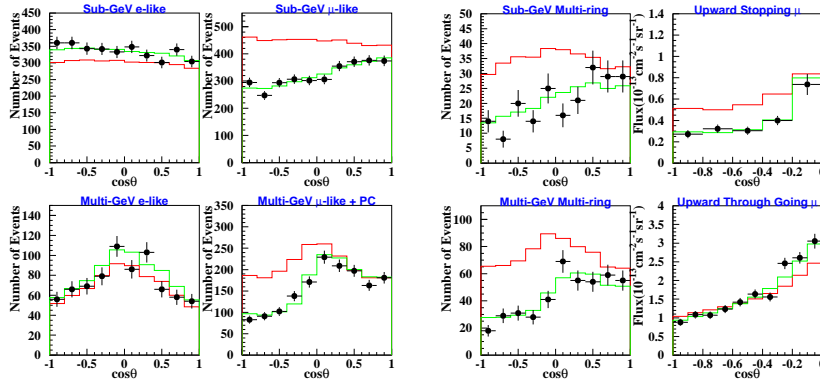


Figure 2. Zenith angle distributions for Super-K’s newest 1489 day atmospheric neutrino samples, including fully-contained events (those with interaction products that do not leave the detector) and partially-contained events (events with an exiting muon), upward through-going and stopping muons (neutrinos interacting below the detector), and multiple ring events (e.g. CC and NC single and multiple pion producing events.) The points with (statistical) error bars are the data; the solid red line represents the MC prediction for no oscillation; the paler green line is the best fit for $\nu_\mu \rightarrow \nu_\tau$ oscillation.

spheric neutrino events. However, recently Super-K has employed several strategies to distinguish $\nu_\mu \rightarrow \nu_\tau$ from $\nu_\mu \rightarrow \nu_s$ ¹². First, one can look for an angular distortion of high-energy neutrinos due to matter effects of sterile neutrinos propagating in the Earth: unlike ν_τ ’s, sterile neutrinos do not exchange Z^0 ’s with matter in the Earth, resulting in a matter effect that effectively suppresses oscillation. The effect is more pronounced at higher energies. Such distortion of the high-energy event angular distribution is not observed. Second, one can look at neutral current (NC) events in the detector: if oscillation is to a sterile neutrino, the neutrinos “really disappear” and do not interact via NC. A NC-enriched sample of multiple-ring Super-K events shows no deficit of up-going NC events. Together, these measurements exclude two-flavor $\nu_\mu \rightarrow \nu_s$ at 99% C. L., for all parameters allowed by the Super-K fully-contained events¹². The maximum allowed admixture of sterile neutrinos is about 20%⁸.

There is one more piece of evidence from Super-K suggesting that $\nu_\mu \rightarrow \nu_\tau$ oscillations are primarily responsible for the observed disappearance^{8,9}. Because the energy threshold for tau production is about 3.5 GeV and only a small fraction of the atmospheric neutrino flux exceeds this energy, only about 90 ν_τ -induced τ leptons are expected in Super-K’s 1489 day sample, given the measured oscillation parameters. Tau leptons decay with a very short lifetime into a variety of modes, and can be observed as ener-

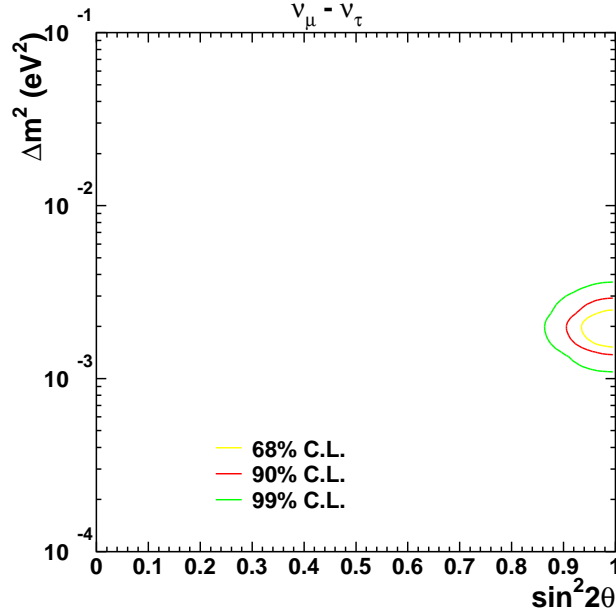


Figure 3. Right: allowed region in oscillation parameter space corresponding to the fit to Super-K atmospheric neutrino data (including fully-contained events, partially-contained events, and upward-going muons.)

getic multi-ring events; such events are very difficult to disentangle from a large background of multi-ring CC and NC events. Nevertheless, three independent Super-K analyses which select “ τ -like” events have determined excesses of up-going ν_τ events consistent with τ appearance at about the 2σ level.

3.1.1. Long Baseline Experiments

The next experiments to explore atmospheric neutrino parameter space are the “long-baseline” experiments, which aim to test the atmospheric neutrino oscillation hypothesis directly with an artificial beam of neutrinos. In order to achieve sensitivity to the oscillation parameters indicated by Super-K, L/E must be such that for ~ 1 GeV neutrinos, baselines are hundreds of kilometers. A beam is created by accelerating protons and bombarding a target to produce pions and other hadrons; pions are then focused forward with a high-current magnetic “horn” and allowed to decay in a long pipe. The neutrino flavor composition and spectrum can be measured in a near

detector before propagation to a distant far detector.

The first long-baseline experiment is the K2K (KEK to Kamioka) experiment¹³, which started in March 1999, and which saw the first artificial long-distance neutrinos in June 1999. K2K sends a beam of $\langle E_\nu \rangle \sim 1$ GeV ν_μ 250 km across Japan to the Super-K experiment. K2K can look for ν_μ disappearance (the beam energy is not high enough to make significant numbers of τ 's.) Preliminary K2K results^{13,14} do show a deficit of observed neutrinos: $80.1^{+6.2}_{-5.4}$ beam events in the fiducial volume are expected, based on beam-modeling and near detector measurements; however only 56 single-ring ν_μ events were seen at Super-K. The far spectrum was also measured. The best fit oscillation parameters using both spectrum and suppression information are entirely consistent with the atmospheric results. See Figure 4. Somewhat more than half of K2K data has now been taken. The beam resumed in early 2003 after repair of Super-K. The next generation long baseline experiments will be discussed in Section 5.3.

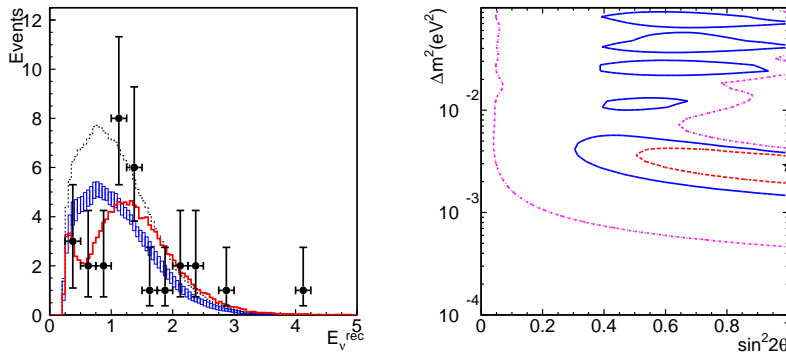


Figure 4. Left: Expected beam neutrino spectrum for no oscillations (dashed line), data (points), expected spectrum with systematic error normalized to the number of observed events (boxes) and best fit to the oscillation hypothesis (solid) for the K2K 1999-2001 data sample. Right: allowed region in oscillation parameter space corresponding to K2K 1999-2001 data sample, using both suppression and spectrum.

3.2. Solar Neutrinos

The deficit of solar neutrinos was the first experimental hint of neutrino oscillations. The solar neutrino energy spectrum is well-predicted, and depends primarily on weak physics, being rather insensitive to solar physics.

The three “classic” solar neutrino detectors (chlorine, gallium and water Cherenkov), with sensitivity at three different energy thresholds, together observe an energy-dependent suppression which cannot be explained by any solar model (standard or non-standard)¹⁵.

The observed suppression in all three experiments can be explained by neutrino oscillation at certain values of Δm^2 and mixing angle: see Figure 5. The “classic” allowed regions at higher values of Δm^2 (“small mixing angle”, “large mixing angle” and “low”) are those for which matter effects in the Sun come into play. There are also solutions at very small Δm^2 values for which matter effects in the sun are not involved: these are known as “vacuum” oscillation or “just-so” solutions.^c Figure 5 shows the mixing angle axis plotted as $\tan^2 \theta$, rather than as the more conventional $\sin^2 2\theta$, to make evident the difference between $0 < \theta < \pi/4$ and $\pi/4 < \theta < \pi/2$: these regions are not equivalent when one considers matter effects¹⁶.

Before 2000, the most precise real-time solar neutrino data came from Super-K via the elastic scattering reaction $\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$, which proceeds via both CC and NC channels, with a cross-section ratio of about 1:6. In this reaction, the Cherenkov light of the scattered electron is measured. The scattered electrons point away from the direction of the sun.

Possible “smoking guns” for neutrino oscillations include a distortion from the expected shape that would be hard to explain by other than non-standard weak physics. The latest Super-K solar neutrino spectrum shows no evidence for distortion¹⁷. Another “smoking gun” solar neutrino measurement is the day/night asymmetry: electron neutrinos may be regenerated in the Earth from their oscillated state for certain oscillation parameters. The latest measured Super-K day/night asymmetry is $\frac{day-night}{(day+night)/2} = -0.021 \pm 0.020_{stat}^{+0.013}_{-0.012}$ (syst): regeneration is therefore a relatively small effect, if it is present at all. Together, the energy spectrum and day/night observations place strong constraints on solar neutrino parameters. In particular, Figure 5 shows the Super-K results overlaid on the global flux fit parameters: large mixing angles are favored, and the small mixing angle and vacuum solutions from the global flux fit are disfavored at 95% C.L.. Global flux fit $\nu_e \rightarrow \nu_s$ solutions are also disfavored.

The information from Super-K served primarily to constrain parame-

^cThe vacuum solutions are “just-so” because oscillation parameters must fine-tuned to explain suppression at exactly the Earth-Sun distance; on the other hand, because the Sun has a range of electron densities, ν_e suppression will result for a broader range of oscillation parameters if one assumes that matter effects are involved.

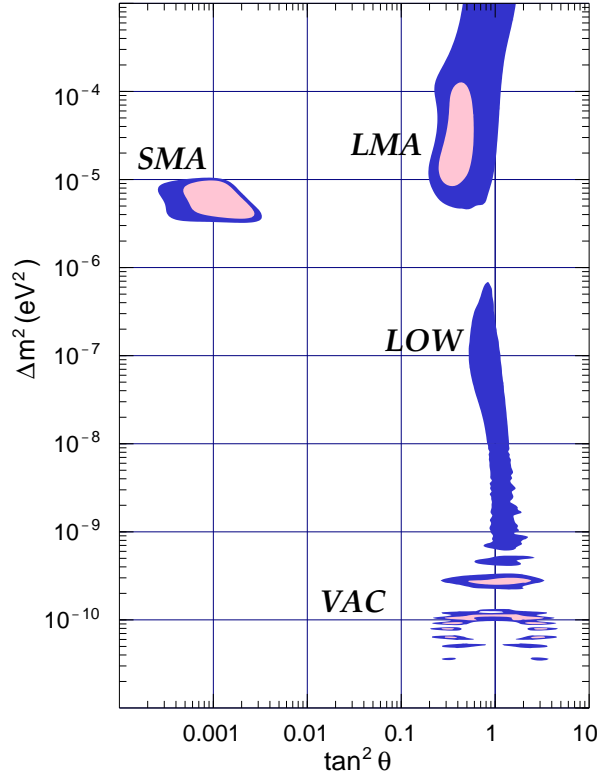


Figure 5. Solar neutrino parameter space: the shaded areas show the “classic” global flux fit solutions from chlorine, gallium and water Cherenkov experiments (from Reference ¹⁶.)

ters. The true “smoking gun” for solar neutrino oscillations recently came from the Sudbury Neutrino Observatory¹⁸, a detector comprising 1 kton of D₂O in Sudbury, Canada, with the unique capability to detect neutral current reactions from the breakup of deuterium, $\nu_x + d \rightarrow \nu_x + p + n$: since this reaction is flavor-blind, it measures the *total* active neutrino flux from the sun. Neutrons from this reaction can be detected via various methods: capture on *d* itself, capture on Cl ions from dissolved salt, and neutron detectors. In addition, the charged current reaction $\nu_e + d \rightarrow \nu_e + p + e^-$ specifically tags the ν_e component of the solar flux. SNO also observes the same neutrino-electron elastic scattering (ES) interaction as Super-K, which proceeds via both CC and NC channels.

SNO’s recent results¹⁹ are summarized in Figure 7, which shows the

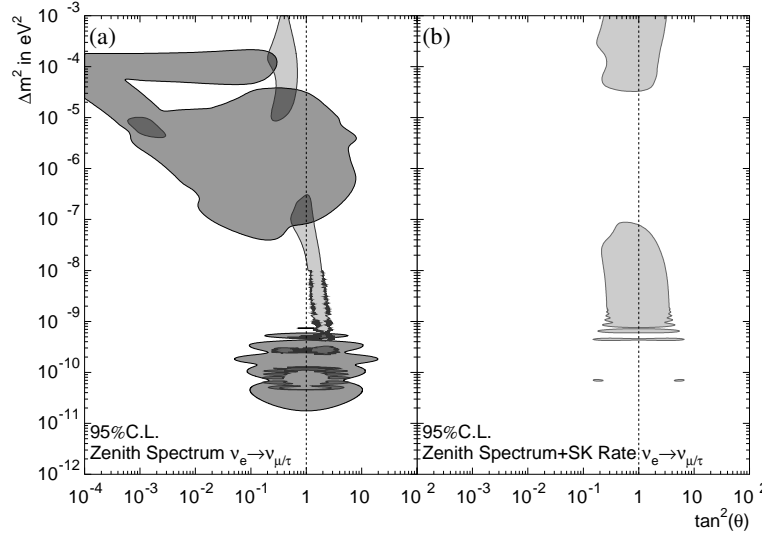


Figure 6. Solar neutrino parameter space: on the left, the light grey areas show the “classic” global flux fit solutions from chlorine, gallium and the SNO experiment’s CC measurement. The darker grey shaded regions indicate Super-K’s excluded regions from spectral and day/night information (and the darkest grey regions indicate the overlap.) On the right, the light shaded areas indicate allowed regions from Super-K data alone and SSM ^8B neutrino flux.

measured fluxes $\phi_{\mu\tau}$ vs ϕ_e .^d The CC measurement, which tags ν_e flux ϕ_e , is represented by a vertical bar on this plot. Since the neutral current flux is flavor-blind and therefore represents a measurement of the sum of $\phi_{\mu\tau}$ and ϕ_e , *i.e.* $\phi_{NC} = \phi_{\mu\tau} + \phi_e$, the NC measurement corresponds to a straight line with slope -1 on this plot. The intersection with the vertical CC line indicates the composition of the solar neutrino flux: it is approximately $1/3 \nu_e$ and $2/3 \nu_{\mu,\tau}$. The ES reaction measures both ν_e and $\nu_{\mu,\tau}$ with a known ratio, $\phi_{ES} = 0.154\phi_{\mu\tau} + \phi_e$ for SNO, so that the ES measurement corresponds to a line on the plot with slope $-1/0.154$; it provides a consistency check. The conclusion from SNO is that solar neutrinos *really are oscillating* (into active neutrinos.) The solar neutrino problem is solved!

The detailed measurements from SNO incorporating observed day/night asymmetry and energy spectra shrink the allowed parameters down to small

^dNote that one cannot distinguish between ν_μ and ν_τ at low energy since the NC interaction does not distinguish between them.

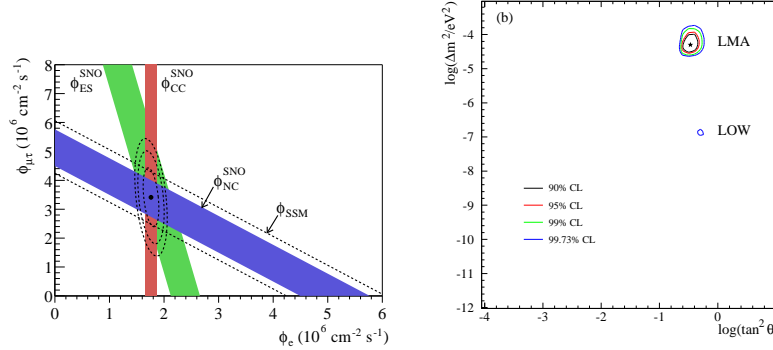


Figure 7. Left: Inferred flavor components from fluxes measured at SNO (see text.) Right: allowed region in oscillation parameter space after SNO 2002 results.

regions, shown in Figure 7. At 99% C.L., only the LMA region is left.

So far, SNO's NC measurement comes from capture of neutrons on d ; SNO continues to run, and will provide cross-checked NC measurements using salt and helium neutron counters.

There is one more recent chapter in the solar neutrino story. KamLAND, a 1 kton scintillator detector at the Kamioka mine in Japan²⁰, has investigated solar neutrino oscillation parameters using reactor neutrinos rather than solar neutrinos directly. Reactors produce $\bar{\nu}_e$ of few-MeV energies abundantly; assuming vacuum oscillations, the baseline required to observe oscillations with LMA parameters is about ~ 100 km. Note that no significant matter effects are expected at this baseline. KamLAND observes the sum of the fluxes of neutrinos from reactors in Japan and Korea, with roughly a 180 km average baseline, via the inverse beta decay reaction $\bar{\nu}_e + p \rightarrow e^+ + n$; $\bar{\nu}_e$'s are tagged using the coincidence between the positron and the 2.2 MeV γ -ray from the captured neutron. In December 2002, the KamLAND experiment announced an observed suppression of reaction $\bar{\nu}_e$ consistent with LMA parameters: see Figure 8. Solar neutrino oscillations are therefore now confirmed using a completely independent source of neutrinos and experimental technique. In addition, the LMA solution is strongly indicated.

3.3. LSND

The third oscillation hint is the only ‘‘appearance’’ observation: the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos has ob-

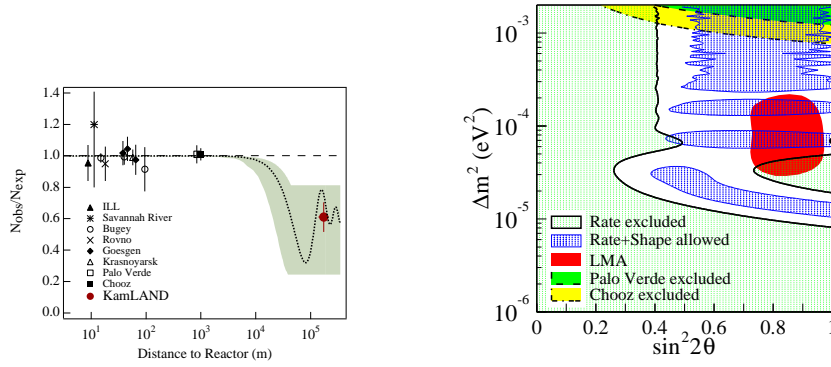


Figure 8. Left: Ratio of measured to expected $\bar{\nu}_e$ for various experiments as a function of baseline; the point on the far right is the KamLAND result. The shaded area represents the expectation from the solar LMA solution, and the dotted line is the best fit to the oscillation hypothesis. Right: Allowed and excluded regions in oscillation parameter space for various experiments (as indicated in the legend.)

served an excess of $\bar{\nu}_e$ events²¹ from a beam which should contain only $\bar{\nu}_\mu$, ν_e and ν_μ from positive pion and muon decay at rest. The result is interpreted as ~ 20 - 50 MeV $\bar{\nu}_\mu$'s oscillating over a 30 m baseline. See Figure 9 for the corresponding allowed region in parameter space, which is at large Δm^2 and small mixing. (The large mixing angle part of this range is ruled out by reactor experiments.)

An experiment at Rutherford-Appleton Laboratories in the U. K. called KARMEN, which has roughly similar neutrino oscillation sensitivity as does LSND (although with a shorter 17.5 m baseline), does not however confirm the LSND result²². This detector expects fewer signal events than does LSND, but has a stronger background rejection due to the pulsed nature of the ISIS neutrino source. However, due to somewhat different sensitivity, KARMEN's lack of observation of $\bar{\nu}_e$ appearance cannot rule out all of the parameter space indicated by LSND: see Figure 9.

4. Where Do We Stand?

Now we can step back and view the big picture. Where do we stand? The current experimental picture for the three oscillation signal indications can be summarized:

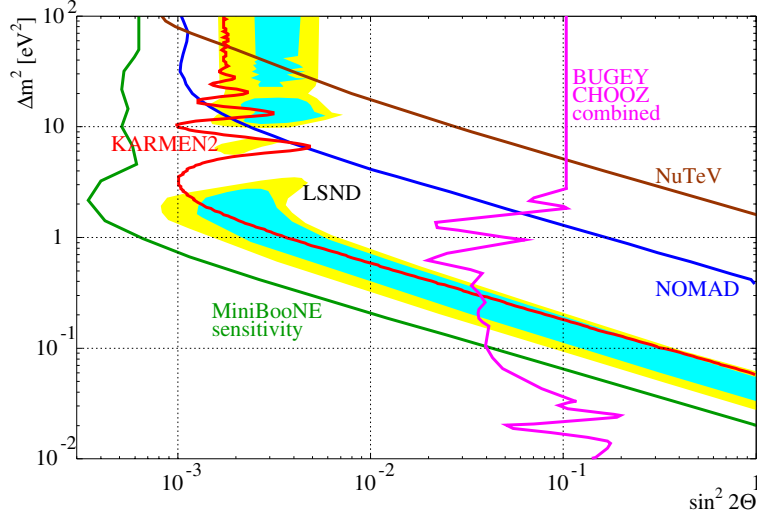


Figure 9. The shaded region shows the LSND allowed regions at 90% and 99% C.L.; the region to the right of the KARMEN2 line is excluded by KARMEN. Also shown are exclusions by the reactor experiments Bugey and Chooz, the NuTeV and Nomad excluded regions, and the reach of the mini-BooNE experiment (see Section 5.1.)

- For atmospheric neutrino parameter space: evidence from Super-K, Soudan 2 and MACRO is very strong for $\nu_\mu \rightarrow \nu_x$. Furthermore, Super-K's data favor the $\nu_\mu \rightarrow \nu_\tau$ hypothesis over the $\nu_\mu \rightarrow \nu_s$ one. These oscillation parameters have been independently confirmed using the K2K beam of ~ 1 GeV ν_μ 's to Super-K.
- For solar neutrino parameter space ($\nu_e \rightarrow \nu_x$): The solar neutrino problem is now solved. While Super-K data favored large mixing via day/night and spectral measurements, SNO's D₂O-based NC and CC measurements have confirmed that solar neutrinos are oscillating, and have shrunk down the allowed parameter space to the LMA region using day/night and spectral measurements. Better yet, the KamLAND experiment has independently confirmed the LMA solution using reactor $\bar{\nu}_e$'s. Oscillation to sterile neutrinos is disfavored.
- The LSND indication of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ still stands; KARMEN does not rule out all of LSND's allowed parameters.

What do these data mean? There is an obvious problem. Under the assumption of three generations of massive neutrinos, there are only two

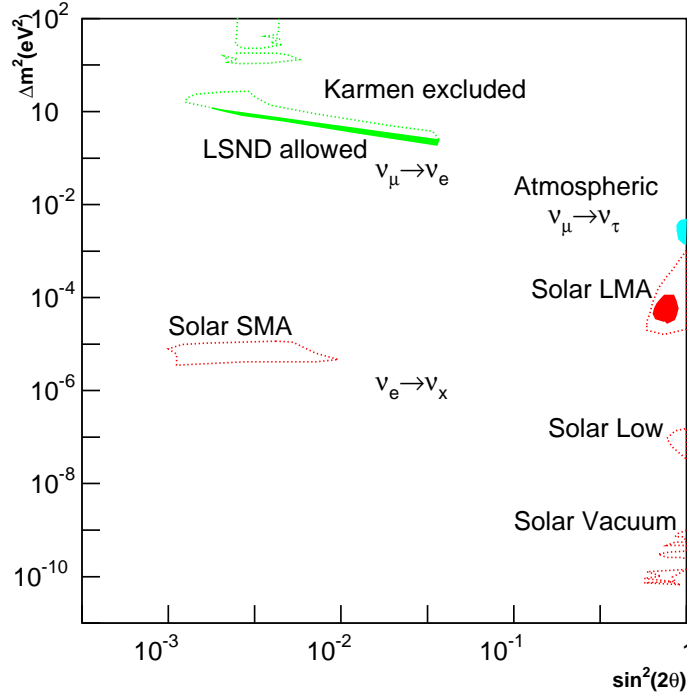


Figure 10. Oscillation parameter space showing all three indications of oscillation, in the two-flavor mixing approximation. At high Δm^2 , the parameters allowed by LSND are shown by dotted lines, and the part not excluded by Karmen is shown as a solid region. Allowed atmospheric neutrino parameters are shown at large mixing and Δm^2 of about $2.5 \times 10^{-3} \text{ eV}^2$. Also shown by dotted lines are the “classic” solar neutrino solutions at small Δm^2 : “small mixing angle” (SMA), “large mixing angle” (LMA), and “low”, which all involve matter effects in the sun, and the vacuum solutions at very small Δm^2 . With new information from SNO and KamLAND, only the LMA solution is now allowed, as indicated by the solid region at about $4.5 \times 10^{-4} \text{ eV}^2$.

independent values of Δm_{ij}^2 : we must have $\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$. However, we have three measurements which give Δm_{ij}^2 values of three different orders of magnitude. So, if each hint represents two-flavor mixing, then something must be wrong. All data cannot be satisfactorily fit assuming three-flavor oscillations. One way to wriggle out of this difficulty is to introduce another degree of freedom in the form of a sterile neutrino (or neutrinos) or else invoke some exotic solution (*e.g.* CPT violation²⁵.) (We cannot introduce another active neutrino, due to the Z^0 width measure-

ments from LEP, which constrain the number of light active neutrinos to be three²³: any new light neutrino must be sterile.) Although pure mixing into ν_s is now disfavored by solar and atmospheric neutrino results, a sterile neutrino is still barely viable as part of some four-flavor mixing²⁴. Of course, it is also possible that some of the data are wrong or misinterpreted. Clearly, we need more experiments to clarify the situation.

5. What's Next for Two-flavor Oscillations?

So what's next? First, let's consider the next experiments for each of the interesting regions of two-flavor parameter space.

5.1. *LSND Neutrino Parameter Space*

The next experiment to investigate the LSND parameter space will be BooNE (Booster Neutrino Experiment.) This will look at ~ 1 GeV neutrinos from the 8 GeV booster at Fermilab, at a baseline of about 500 m (with a second experiment planned at longer baseline if an oscillation signal is seen.) This experiment is primarily designed to test $\nu_\mu \rightarrow \nu_e$ at about the same L/E as LSND. Since the neutrino energy is higher, and the backgrounds are different, systematics will presumably be different from those at LSND. BooNE, which started in 2002, expects to cover all of LSND parameter space²⁶ (see Figure 9.) If a signal is found, the BooNE collaboration plans to build another detector at a longer baseline to further test the oscillation hypothesis.

5.2. *Solar Neutrino Parameter Space*

Now that the latest results from SNO and KamLAND have squeezed the allowed solar mixing parameters down to the LMA region, solar neutrino physics is entering a precision measurement era. Over the next few years, we expect to have cross-checks of NC measurements from SNO, using different neutron detection techniques (salt, NCDs.) From KamLAND we expect better precision from improved statistics and systematics; KamLAND will also attempt to measure the solar neutrino flux directly. Borexino, a planned 300 ton scintillator experiment at the Gran Sasso Laboratory in Italy²⁷ with very low radioactive background, hopes to measure the solar ${}^7\text{Be}$ line at 0.86 MeV.

The true frontier for solar neutrino experiments is the real-time, spectral measurement of the flux of neutrinos below 0.4 MeV produced by pp

reactions in the sun, which are responsible for most of the solar energy generation. The pp flux is precisely known, which will aid in precision measurements of mixing parameters; in addition if the total pp flux is well-known, measurement of the active component will help constrain a possible sterile admixture. The pp flux is also a new window on solar energy generation. Because the pp flux is very large, one can build relatively small (tens to hundreds of tons) detectors and still expect a reasonable rate of neutrino interactions. The challenge is to achieve low background at low energy threshold. There are a number of innovative new solar neutrino experiments aiming to look at the very low energy pp solar flux²⁸, among them LENS, Heron, solar-TPC and CLEAN.

5.3. *Atmospheric Neutrino Parameter Space*

Two-flavor oscillation studies at atmospheric neutrino parameters has also entered a precision measurement era.

The K2K experiment will continue, now that Super-K has been refurbished to 47% of its original number of inner detector phototubes after the accident of November 2001. The results published so far represent about half of the total number of protons on target for the neutrino beam; the next few years will see both systematic and statistical precision improvements in mixing parameter measurements.

The next set of long baseline experiments to explore atmospheric oscillation parameter space have ~ 730 km baselines and will start in a few years. The NuMi beamline³¹ will send a ν_μ beam from Fermilab to Soudan, with a beam energy of 3 – 8 GeV, and a baseline of 735 km. The far detector, MINOS²⁹ is a magnetic iron tracker. A primary goal is to attain 10% precision on 2-3 mixing parameters Δm_{23}^2 and $\sin^2 2\theta_{23}$.

CNGS (Cern Neutrinos to Gran Sasso)³⁰ is a ~ 20 GeV ν_μ beam from CERN to the Gran Sasso 730 km away. The two planned CNGS detectors, OPERA³² and Icarus³³, are focused on an explicit ν_τ appearance search. Because when τ 's decay they make tracks only about 1 mm long, both detectors are fine-grained imagers. Icarus is a liquid argon time projection chamber, and OPERA is a hybrid emulsion/scintillator detector. Both experiments expect a few dozen τ events over several years of running.

6. Beyond Two-Flavor Oscillations

The previous section discussed the future of neutrino oscillation studies in the context of two-flavor oscillations. As noted in section 2, however, this

is an approximation valid for well-separated mass states, which appears to be the case. However a full description requires three flavors.

In the following, we will assume that a “standard” three-flavor picture is valid. If mini-BooNE confirms the LSND effect, we will have to rethink our picture, and our goals.

In this “standard” picture, neutrino mixing can be described by six parameters: two independent Δm_{ij}^2 (Δm_{12}^2 , Δm_{23}^2), three mixing angles (θ_{12} , θ_{23} , θ_{13}), and a CP violating phase δ .^e The mixing matrix U of equation 2 can be written as a product of three Euler-like rotations, each described by one of the mixing angles:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (4)$$

where “ s ” represents sine of the mixing angle and “ c ” represents cosine.

The “1-2” matrix describes solar mixing; the “2-3” matrix describes atmospheric neutrino mixing. The “1-3” or “e3” mixing is known to be small; θ_{13} may be zero. The mass-squared difference $\Delta m_{23}^2 \sim 2 \times 10^{-3} \text{ eV}^2$ describes the atmospheric mixing, and $\Delta m_{12}^2 \sim 4.5 \times 10^{-5} \text{ eV}^2$ describes solar mixing. Neutrino oscillation experiments tell us only about mass-squared differences; the absolute mass scale is known only to be less than about 2 eV. It is also as yet unknown whether the mass hierarchy is “normal”, *i.e.* the solar mixing is described by two lighter states, or “inverted”, *i.e.* the solar mixing is described by two heavier states (see Figure 11.)

The remaining questions can be addressed by neutrino oscillation experiments are:

- Is U_{e3} non-zero?
- Is the hierarchy normal or inverted?
- Is 2-3 mixing maximal, or just large?
- Is the CP-violating phase non-zero?

6.1. The Next Step: $e3$ Mixing

The next question which can be approached experimentally is that of $e3$ mixing. A consequence of a non-zero U_{e3} matrix element will be a small

^eMajorana phases, which cannot be measured in oscillation experiments and in general are very difficult to observe³⁴, will not be considered here.

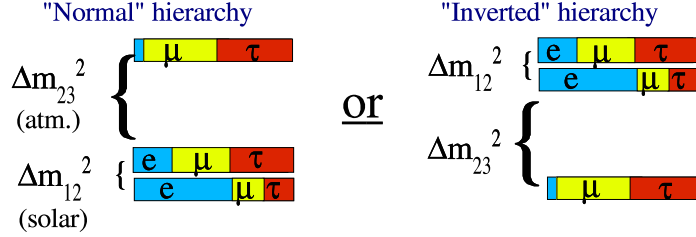


Figure 11. Normal and inverted hierarchies in the three-flavor picture, with mass-squared values of the three states indicated vertically, and possible flavor composition of the mass states indicated by the horizontal divisions.

appearance of ν_e in beam of ν_μ : for $\Delta m_{23}^2 \gg \Delta m_{12}^2$ (as is the case), and for $E_\nu \sim L\Delta m_{23}^2$, ignoring matter effects we find

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(1.27\Delta m_{23}^2 L/E). \quad (5)$$

This expression illustrates that θ_{13} manifests itself in the amplitude of an oscillation with 2-3-like parameters. Since ν_e appearance has never been observed at these parameters, this amplitude (and hence θ_{13}) must be *small*. The best limits so far, shown in Figure 12, come from a reactor experiment, CHOOZ, which observed no disappearance of reactor $\bar{\nu}_e$.^f The on-axis long baseline experiments mentioned in section 3.1.1 can likely improve this limit by a factor of approximately five. To do better than this is a difficult job: since the modulation may be parts per thousand or smaller, one needs both good statistics and low background data. The primary sources of background for a long baseline experiment are: intrinsic beam ν_e contamination, misidentified NC resonant π^0 production (since π^0 decay to γ -rays which make electron-like showers), and other misidentified particles.

6.1.1. Off-Axis Beams

A promising next step for measurement of θ_{13} (assuming it is large enough to be measured) is an off-axis detector at a long baseline neutrino beam. An

^fIn the literature one finds limits and sensitivities to this mixing angle variously expressed in terms of θ_{13} (in radians or degrees), $\sin \theta_{13}$, $\sin^2 \theta_{13}$, $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{\mu e}$, $|U_{e3}|$, or $|U_{e3}|^2$; no convention has yet emerged. For $\Delta m_{12}^2 \ll \Delta m_{23}^2 \sim \Delta m_{13}^2$, $\sin^2 2\theta_{\mu e} \equiv \sin^2 2\theta_{13} \sin^2 \theta_{23}$ is the measured ν_e appearance amplitude. $|U_{e3}| = \sin \theta_{13}$, and for $\theta_{23} \sim \pi/4$ and θ_{13} small, it follows that $\sin^2 2\theta_{\mu e} \sim \frac{1}{2} \sin^2 2\theta_{13} \sim 2 \sin^2 \theta_{13}$.

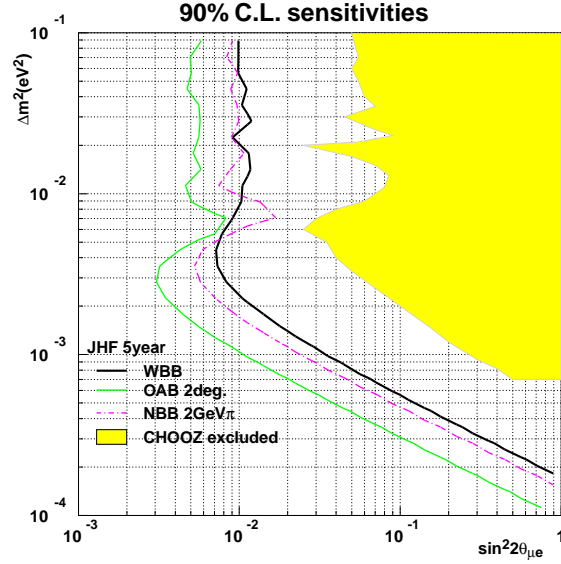


Figure 12. Expected sensitivity to $\sin^2 2\theta_{13}$ with J-PARCnu, for various beam configurations (a 2° off-axis configuration, labeled OAB 2deg on the plot, has been selected.) The CHOOZ excluded region for $\bar{\nu}_e$ disappearance is shown for comparison. NuMi off-axis and new reactor experiments have comparable sensitivity.

experiment placed a few degrees off axis has some kinematic advantages. Because two-body pion decay kinematics imply that neutrino energy becomes relatively independent of pion energy off-axis, the neutrino spectrum becomes more sharply peaked. Therefore an off-axis siting is favorable for background reduction and oscillation fits, in spite of the reduction in ν flux.

There are two major long-baseline off-axis detector projects currently under consideration. The first of these is J-PARCnu³⁶, comprising a high power (0.77 MW) beam from the J-PARC facility in Japan (currently under construction.) The far detector, 2° off-axis, will be a fully refurbished Super-K at 295 km. The second off-axis proposal³⁷, for the U.S., is to exploit the NuMi beam which will exist for MINOS, and build a new detector off-axis at a distance of 700-900 km. Various detector technologies and sites are under discussion. Sensitivity to θ_{13} for both possibilities will be roughly a factor of 10-20 better than the CHOOZ limit.

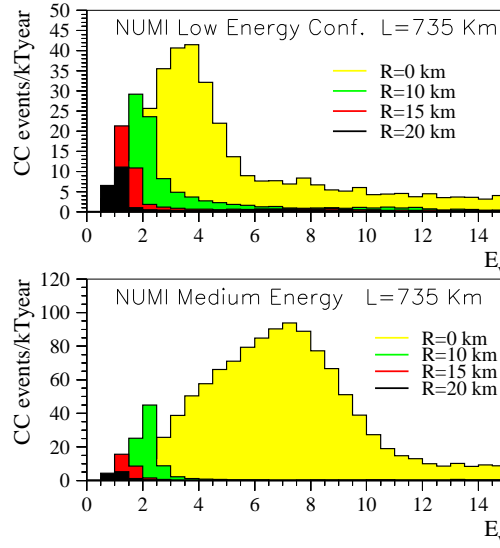


Figure 13. Expected CC interaction spectra for various off-axis locations for low and medium-energy NuMI beams, from Reference ³⁵.

6.1.2. Reactor Experiments

Another possibility currently under consideration by groups in Russia, Japan and the U.S. is an upgraded reactor experiment employing the same strategy as CHOOZ, i.e. search for disappearance of $\bar{\nu}_e$ ³⁸. The challenge for this type of experiment is reduction of systematics to the level where a few percent or smaller modulation is evident. Multiple detectors may help to achieve this.

6.2. Leptonic CP Violation and Mass Hierarchy

The long-term goal of long baseline oscillation experiments in the observation of CP violation in the lepton sector. The basic idea is to measure a difference between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transition probabilities. However, it is not simple to extract a CP violating phase from the measurements: transition rates depend on all MNS matrix parameters, and in addition are affected by the presence of matter.

Following the analysis of Reference ³⁹: the approximate transition probabilities for neutrinos and antineutrinos (assuming θ_{13} , $\Delta_{12}L$ and Δ_{12}/Δ_{13}

are all small) are:

$$\begin{aligned}
 P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp} \right)^2 \sin^2 \left(\frac{\tilde{B}_\mp L}{2} \right) \\
 & + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A} \right)^2 \sin^2 \left(\frac{AL}{2} \right) \\
 & + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_\mp} \sin \left(\frac{AL}{2} \right) \sin \left(\frac{\tilde{B}_\mp L}{2} \right) \cos \left(\pm \delta - \frac{\Delta_{13} L}{2} \right),
 \end{aligned} \tag{6}$$

where

$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}, \tag{7}$$

L is the baseline, $\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}$, $\tilde{B}_\mp \equiv |A \mp \Delta_{13}|$, and A is the matter parameter $A = \sqrt{2}G_F N_e$, where G_F is the Fermi constant and N_e is the electron density of the matter traversed. The upper sign in \pm refers to neutrinos and the lower to antineutrinos. The first two terms are the “non-CP” terms and the last term depends on the CP-violating phase.

A few observations about observability of leptonic CP violation may be made based on this expression:

- The fact that $\sin^2 2\theta_{12}$ is large, as recently indicated by SNO and KamLAND, is good news: the CP term is proportional to $\sin 2\theta_{12}$.
- The CP terms are proportional to $\sin 2\theta_{13}$; therefore a very small value of θ_{13} will mean that CP violation will be very difficult to observe.
- Precision measurements of all parameters will be necessary for measurement of CP observables!
- Matter effects cause a fake asymmetry between neutrinos and antineutrinos, as indicated by the matter terms (see Figure 14 from Reference ³⁵.) This may be considered a blessing rather than a curse, because the sign of the neutrino/antineutrino asymmetry depends on the sign of Δm^2 . In other words, one can learn about the mass hierarchy by measuring the asymmetry. Observation of matter effects requires relatively long baselines (typically more than 500 km, depending on parameters.)
- Parameter ambiguities from various sources are intrinsic to these equations, and a single measurement will not suffice to measure both δ and θ_{13} (and matter effects.) For instance, consider Fig-

ure 15 drawn from Reference ⁴⁰, which shows probability of transition for antineutrinos versus probability of transition for neutrinos (the axes represent the observables.) For a given value of $\sin^2 2\theta_{13}$, one can draw an ellipse corresponding to different values of δ ; this ellipse is shifted for different hierarchies via the matter effect. In consequence, one must make multiple measurements with different experimental parameters in order to resolve the ambiguities. Some of these issues are explored in *e.g.* References ^{40,41}.

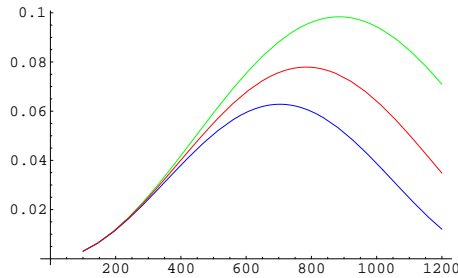


Figure 14. Transition probabilities for neutrinos (green, top curve) and anti-neutrinos (blue, bottom curve) in matter and vacuum (red, middle curve) as function of the distance for 2 GeV, $\Delta m_{13}^2 = 3 \times 10^{-3} \text{ eV}^2$ (normal hierarchy), $\theta_{23} = \pi/4$, $\Delta m_{12}^2 = 1 \times 10^{-4} \text{ eV}^2$, $\theta_{23} = \pi/6$, $|U_{e3}|^2 = 0.04$, and $\delta = 0$. Figure from Reference ³⁵.

Assuming that θ_{13} is large enough for there to be some hope of observing leptonic CP violation, the obvious strategy is an upgraded long baseline experiment, perhaps as a “Phase II” of an off-axis program, or perhaps as an on-axis detector program such as the proposed broad-band beam from Brookhaven⁴². Very large detectors (e.g. the 1 Mton Hyper-K detector) and upgraded “superbeams” have been proposed^{36,42,43,44}. As mentioned above, multiple measurements with differing energies and/or baselines, with both neutrinos and antineutrinos will be necessary for full characterization of the parameters.

More ambitious alternatives to a traditional proton-induced neutrino superbeam have been proposed. For instance a muon storage ring “neutrino factory” would produce copious, and well-understood, 20-50 GeV neutrinos from muon decay⁴⁵. Detectors at 3000-7000 km could explore matter effects. However this idea is for the rather distant future due to high cost and technical difficulties to be overcome. Other interesting ideas include a “beta-beam” of radioactive ions which could provide a high flux of $\bar{\nu}_e$ ’s^{46,47}.

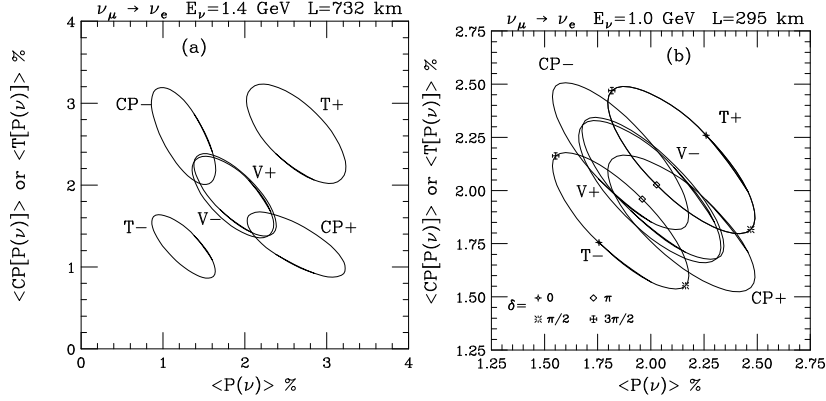


Figure 15. The T (CP) trajectory diagrams (ellipses) in the plane $P(\nu_\mu \rightarrow \nu_e)$ versus $P(\nu_e \rightarrow \nu_\mu)$ ($P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$) for an average neutrino energy (spread 20%) and baseline of (a) 1.4 GeV and 732 km (NUMI/MINOS) and (b) 1.0 GeV and 295 km (J-PARCnu.). The ellipses labeled with a T and CP are in matter with a density times electron fraction given by $Y_e \rho = 1.5 \text{ g cm}^{-3}$ whereas those ellipses labeled V are in vacuum where the T and CP trajectories are identical. The plus or minus indicates the sign of Δm_{31}^2 . The mixing parameters are fixed to be $|\Delta m_{31}^2| = 3 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{23} = 1.0$, $\Delta m_{21}^2 = +5 \times 10^{-5} \text{ eV}^2$, $\sin^2 2\theta_{12} = 0.8$ and $\sin^2 2\theta_{13} = 0.05$. The marks on the CP and T ellipses are the points where the CP or T violating phase $\delta = (0, 1, 2, 3)\pi/2$ as indicated. See Reference ⁴⁰ for details.

7. Non-Oscillation Neutrino Physics

So far this review has focused on neutrino oscillation studies. However, oscillation physics hardly comprises all of neutrino physics. Perhaps the two most compelling experimental questions that cannot be answered by oscillation experiments are:

- What is the absolute mass scale? We do not know whether the masses are hierarchical or degenerate. This question is fundamental, and additionally has profound consequences for cosmology⁴⁷.
- Are neutrinos Majorana or Dirac? In other words, are they their own antiparticles, described by a two-component spinor, or described by a 4-component Weyl spinor? The answer to this question has tremendous implications for the construction of theory describing neutrino masses. For instance, the “see-saw” mechanisms for neutrino mass generation³ require the neutrino to be Majorana.

In the following sections I will very briefly review experiments which aim to answer some, or both, of these questions. In lieu of detailed discussion,

I will point to comprehensive reviews where possible.

7.1. *Kinematic Neutrino Mass Experiments*

As noted above, neutrino oscillation measurements say nothing about absolute masses of the mass states. The idea behind kinematic neutrino mass searches is simple: look for missing energy. The traditional tritium beta decay spectrum endpoint experiments now have limits for absolute $\bar{\nu}_e$ mass from the Mainz and Troitsk experiments of $\lesssim 3$ eV⁴⁸, and there are some prospects for improvement down to the sub-eV level by the Katrin⁴⁹ experiment. Some new techniques are under consideration, too⁵⁰. The ν_μ and ν_τ mass limits are currently 190 keV⁵¹ and 15.5 MeV⁵² respectively; however improving these direct ν_μ and ν_τ measurements seems less compelling if information about differences between the mass states is available from oscillation experiments.

7.2. *Double Beta Decay*

Another way of getting at absolute neutrino mass, and, in one fell swoop, determine that the neutrino is Majorana, is to discover neutrinoless double beta decay, $(N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^-$. Such a decay is only possible if the neutrino has mass, and is Majorana, as illustrated in Figure 16. The current 90% confidence level lowest mass limits from non-observation of double beta decay are $\langle m_\nu \rangle = |\sum U_{1j}^2 m_{\nu j}| < 0.35$ eV⁴⁸ (note dependence of these limits on the matrix elements.) The current best limits are from ^{76}Ge experiments. Many new double beta decay search experiments are planned and under construction, some employing novel techniques. It appears challenging but not impossible to push the limits down to ~ 0.02 eV⁵³.

7.3. *Neutrino Magnetic Moment*

A non-zero non-transition magnetic moment would imply that neutrinos are Dirac and not Majorana. The best limits on neutrino magnetic moment⁴⁸, in the range $10^{-12} \mu_B$, are astrophysical. The current best laboratory limit, $\mu_{\nu_e} < 1.0 \times 10^{-10} \mu_B$, is from the MUNU experiment⁵⁴, which measures low energy elastic scattering of reactor $\bar{\nu}_e$ on electrons.

7.4. *Supernova Neutrinos*

A supernova is a “source of opportunity” for neutrino physics: we can expect an enormous burst of neutrinos of all flavors from a core collapse in our

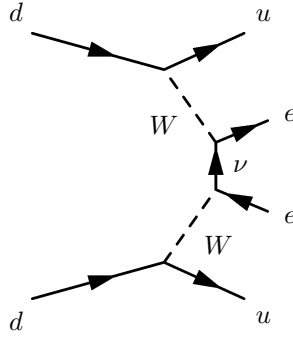


Figure 16. Underlying process of neutrino-less double beta decay, which requires the neutrino to be its own antiparticle.

Galaxy about once every 30 years. Many of the large neutrino experiments – Super-K, SNO, Borexino, KamLAND, LVD and AMANDA, and BooNE – are sensitive⁵⁵ to a burst of supernova neutrinos. Most of these are water or scintillator-based and are primarily sensitive to $\bar{\nu}_e$. In addition to bringing new understanding of stellar core collapse processes, a Galactic supernova would be a tremendous opportunity for neutrino physics. We may be able to extract absolute mass information from time-of-flight-related measurements, although such information, in the best case, may be only marginally better than the best kinematic (and cosmological) limits⁵⁶. Potentially more promising is the information about mixing parameters (θ_{13} and mass hierarchy) that may be inferred from spectra and time-dependence of the different flavor components of the flux⁵⁷: matter-induced flavor transitions in the stellar material, and also in the Earth, may cause inversion of the expected hierarchy of temperatures ($\bar{E}_{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau} > \bar{E}_{\bar{\nu}_e} > \bar{E}_{\nu_e}$) for some mixing parameters and conditions. Therefore detectors with sensitivity to flavors other than $\bar{\nu}_e$ are highly desirable.

The relic supernova neutrinos (neutrinos from past supernovae) have not yet been observed; best limits so far come from Super-Kamiokande⁵⁸.

7.5. Cosmology

Neutrinos are important in cosmology⁵⁹, and play a significant role in big-bang nucleosynthesis and possibly “leptogenesis”, the process by which the matter-antimatter asymmetry of the universe was generated. Ultra low energy (1.95 K) big-bang relic neutrinos are expected to permeate the universe with a number density of 113 cm^{-3} per family. The relic neutrinos must make up some component of the dark matter, although the fraction is

now thought to be small, for consistency with galactic structure formation. Direct detection of these big bang relic neutrinos remains an experimental challenge⁶⁰. However, recent advances in “precision cosmology”^{47,61} are starting to provide quite strong constraints on the properties of neutrinos. The latest cosmic microwave background (CMB) anisotropy data from the WMAP satellite, combined with other CMB experiment data, and other data such as the 2dF Galaxy Redshift Survey, constrain the sum of absolute masses of the neutrino states to be less than ~ 2 eV (depending on assumptions)⁶². These results now rival laboratory kinematic limits, and constrain scenarios involving sterile neutrinos⁶³. There are even prospects for attaining sensitivity to neutrino masses as low as 0.1 eV via precision cosmological measurements (*e.g.* Reference ⁶⁴.)

7.6. *Neutrino Astrophysics*

Very large area long string water Cherenkov detectors (AMANDA, Baikal, Antares, Nestor and the next-generation kilometer-scale IceCube) in ice and water are embarking on a new era of high energy neutrino astronomy⁶⁵. “Cosmic particle accelerators” such as active galactic nuclei and the cataclysmic events that produce gamma-ray bursters, are expected to produce \sim PeV neutrinos, visible in these detectors as upward-going events. Exotic astrophysical sources that produce ultra-high-energy neutrinos may be associated with the highest energy cosmic rays, too. In fact, detectors designed primarily to explore ultra-high-energy cosmic ray air showers will have sensitivity to neutrino-induced “earth-skimming” horizontal air showers⁶⁶. Because the Earth starts to become opaque, via CC interactions, to ν_μ and ν_e at a few hundred TeV, and ν_τ ’s “regenerate” as the CC-induced τ ’s decay, the flavor content of the flux (and the effect of oscillations) can be explored by looking at the angular distribution of observed events. From these neutrinos, we may learn about the physical mechanisms behind the ultra-high-energy sources. Measurement of the relative timing between neutrinos and photons from the same source will test special relativity and the weak equivalence principle.

8. Summary

It is now quite certain that neutrinos have mass and mix: atmospheric and solar oscillation signals are now multiply confirmed and parameters are quite well constrained. The LSND observation does not fit in to the three-flavor picture; we await BooNE to confirm or refute it. If BooNE con-

firms the LSND appearance observation, we will have to begin exploring the possibilities required to explain it. If not, and the standard three-flavor scenario holds, the next steps for neutrino oscillation experiments are clear: search for non-zero θ_{13} , determine the mass hierarchy and ultimately, if parameters are favorable, go for leptonic CP violation. On the non-oscillation front, absolute mass can be approached via kinematic experiments and double beta decay, the latter also promising insight into the Majorana-Dirac question. Precision cosmology is also making headway towards understanding of neutrinos. Knowledge of these parameters is essential for full understanding of matter-antimatter asymmetry of the universe, as well as a full description of the fundamental particles and their interactions. Although this last decade will be a hard act to follow for excitement in neutrino physics, the next decade promises yet more entertainment.

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